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Fabrication and Characterization of Thin Ferroelectric Interferometers for Light Modulation

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ABSTRACT

A thin ferroelectric interferometer (TFI) structure for light modulating devices is presented. It was fabricated entirely with thin film techniques on sapphire and silicon substrates. The ferroelectric layer in this structure was the lanthanum-modified lead zirconate titanate (PLZT) electrooptic material, deposited from a chemical precursor solution onto an ITO-coated dielectric mirror stack. Light intensity modulation in both transmission and reflection modes, and phase modulation in the reflection mode were demonstrated. Experimental and simulation data show that TFI devices can be fast switching with a low driving voltage. Variations of the basic TFI structure can be used for phase tunable spatial light modulators (SLM's) and laser beam steering devices. Design principles, fabrication procedure and the preliminary performance of the devices are described.

Keywords: Spatial light modulator, interferometer, thin film, PLZT

1. INTRODUCTION

High-speed optical modulators that can be integrated with microeletronic components are desirable for applications in optical signal processing and optical interconnects. The majority of the presently existing devices are based on liquid crystal technologies.[1,2] In spite of the technological maturity, liquid crystal materials suffer from slow responding speed, and therefore are unsuitable for systems where fast modulating speeds or large data rates are required. Among the high-speed devices, the best-known kind is the multiple quantum-well (MQW) devices.[3] So far, the MQW-based modulators are limited in usable wavelengths and are incompatible with silicon devices. Some success has been achieved in the integration of complex-oxide ferroelectric materials with silicon for applications in spatial light modulation, which was potentially high-speed.[4,5] Recently, a range of new devices based on the structure of the thin ferroelectric interferometer (TFI) have emerged as promising alternatives that can provide high modulating speed, wide usable wavelength range and ease of monolithic integration with silicon. The TFI structure is comprised of an oxide ferroelectric thin film material sandwiched between two conducting mirrors. A low finesse TFI intensity modulator was first demonstrated on silicon substrate.[6,7] Subsequently, TFI devices with higher finesse were fabricated on both sapphire and silicon substrates.[8-10] In terms of mirror configuration, two mirrors with equal reflectivity have been used to form Febry-Perot structure for optical intensity modulation. In order to apply the TFI device to optical phase modulation, two mirrors with substantially unequal reflectivities can be used. Optical cavities with unequal mirrors are known as Gires-Tournois etalon, from which nearly pure optical phase modulation can be achieved. In this paper, we describe the recent progress in the fabrication of the optical phase modulators based on the TFI structure.

2. FUNDAMENTALS OF TFI PHASE MODULATOR

Both the optical phase modulator array and the beam steering device share the same optical cavity structure shown in Fig. 1. In this structure, the bottom mirror is nearly a total reflection mirror and the top mirror is substantially less reflective, forming a Gires-Tournois etalon. To be used as an optical phase modulator, a light beam is incident on the device from the side of lower reflection mirror. If the wavelength of the light is near a resonance condition with the resonator, the reflected light

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104

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conserves its intensity while experiencing an optical phase shift sensitive to the change of cavity length. Explicitly, the optical phase of the reflected light can be expressed by the following equation:[11]

$$\Phi = -2\tan^{-1}\left(\frac{1+\sqrt{R}}{1-\sqrt{R}}\tan(\Delta\phi)\right),\qquad (1)$$

where R is the reflectivity of the top mirror; $\Delta\phi$ is the deviation of optical length of the spacer (in unit of radian) from a resonance condition, i.e., an integer multiple of $\lambda/2$. In the TFI devices with the Gires-Tournois configuration the deviation $\Delta\phi$ is tunable for a monochromatic incident light. For some complex-oxide ferroelectric materials, a combination of the field-induced index change and the field-induced strain can provide up to 1- percent variation in their total optical path length. According to the above equation, a small field-induced $\Delta\phi$ is amplified by a factor of $(1+\sqrt{R})/(1-\sqrt{R})$ due to the light interference in the etalon, and therefore a large phase shift is obtained in the reflected beam.
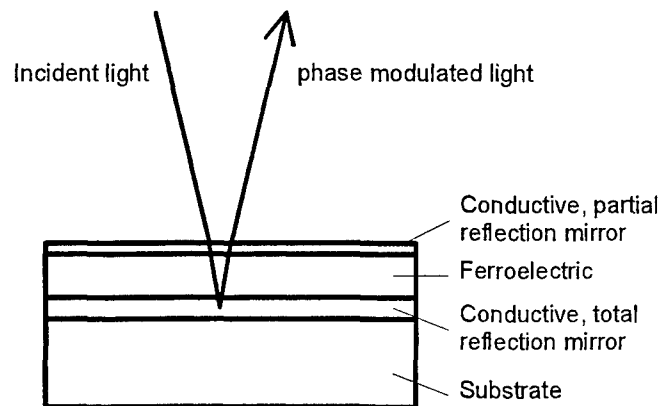

Figure 1. Structure of the TFI optical phase modulator. The two mirrors of unequal reflectivities and the electrooptic ferroelectric thin film form a Gires-Tournois etalon.

One can obtain continuous optical phase modulation in the range of $-\pi$ and π by tuning the Gires-Tournois etalon. With an appropriate reflectivity R for the top mirror, nearly the full 2π phase shift can be generated in the reflected light through the field-induced change in $\Delta\phi$. For example, a 1-μm thick ferroelectric film can create field-induced changes of $\Delta\phi$ in the range of -0.1 and 0.1 radian, which corresponds to an achievable field-induced index change of 0.02 for a visible wavelength. The optical phase modulation one can obtain is plotted in Fig. 2 for different reflectivities of the top mirror.

As shown in Fig. 2, within the attainable $\Delta\phi$, close to a 2π phase shift can be achieved using the ferroelectric thin film material in a Gires-Tournois etalon with top mirror reflectivity R=0.95. For a fixed $\Delta\phi$, the lower the R is the smaller the phase shift becomes. In practice, because of the imperfect bottom mirror (reflectivity close to but less than 100%), the higher the R the more energy loss the reflected light may suffer. Using a multilayer dielectric mirror as the bottom mirror, reflectivity above 99% can be easily obtained. With this bottom mirror, the intensity loss in the reflected light is insignificant even for R=0.95.

Several kinds of high-ε ferroelectric thin film materials have been studied for their use in the TFI devices. These materials include $BaTiO_3$, (Pb,La)(Zr,Ti)O_3 (PLZT) and $Pb(Mg,Nb)O_3$-$PbTiO_3$ (PMN-PT) solid solutions.[12-14] All these thin film materials can be formed by means of the metal-organic chemical liquid deposition (MOCLD) technique or other methods. These thin film materials are usually polycrystalline although quasi-single-crystal films can be formed on lattice-matched substrates. When properly produced, these materials possess high dielectric constant and broad phase transition temperature range, ideal for obtaining large electrooptic coefficients in wide usable temperature ranges. In Fig. 3 the quadratic electrooptic coefficients for most known ferroelectrics, bulk and thin films, are plotted against their dielectric constants in logarithm scales. As one can see, the quadratic electrooptic coefficients appear to be proportional to the dielectric constant squared, ε^2, which can be explained by a theory regarding the electrooptic effects in ferroelectrics.[15] The thin film ferroelectric materials produced in our laboratory typically possess dielectric constant in the range of 1000-3000 and the quadratic electrooptic coefficient in the range of 0.2-2×10^{-16} $(m/V)^2$. Although lower than some bulk materials, these electrooptical coefficients are remarkable for polycrystalline thin film materials.
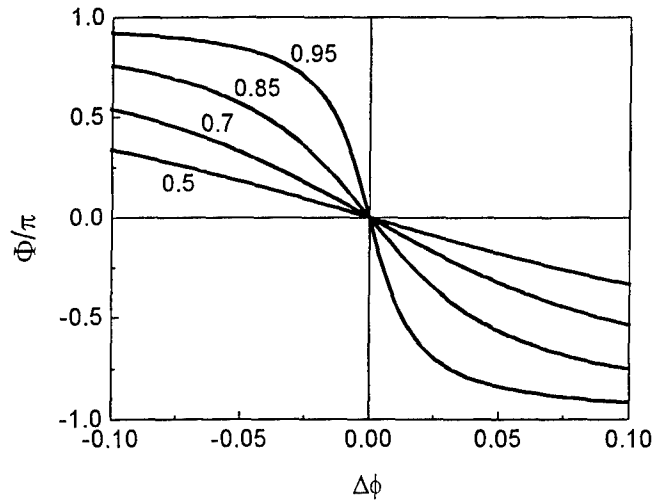
Figure 2. Optical phase of the light beam reflected from a Gires-Tournois etalon with different top mirror reflectivities, R's.
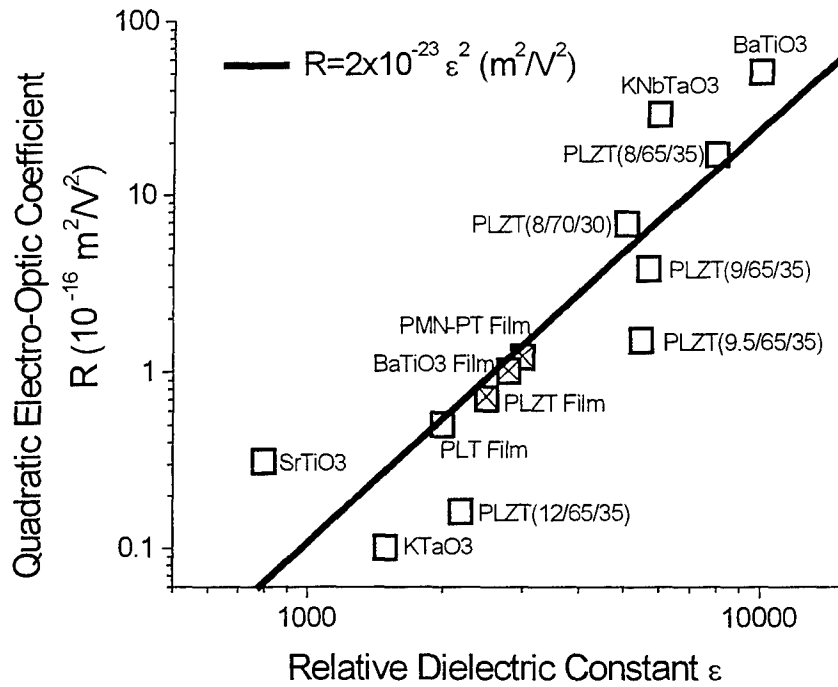

Figure 3. Correlation between the quadratic electrooptic coefficient and the dielectric constant of various ferroelectric materials. The symbol "×" indicates thin film materials produced in our laboratory.

Most of the above mentioned thin film ferroelectric materials are transparent for the entire visible and a range of infrared wavelengths; an example is the PLZT material system with usable wavelength ranging from 400 nm to 6μm.[16] TFI phase modulators using the PLZT materials can be made to modulate laser lights in the wavelength range. The TFI phase modulators are polarization independent as long as the incident angle of the laser beam is small, which can be realized with an appropriate design.

3. FABRICATION OF PHASE MODULATOR

The TFI phase modulators have been successfully fabricated on sapphire substrates. Single-crystal, r-oriented sapphire wafers were used as substrates. The bottom conductive mirror consisted of a quarter-wave dielectric stack with an additional indium-tin oxide (ITO) layer. The top conductive mirror had a similar structure as the bottom mirror except that the ITO layer was deposited prior to the dielectric stack. Both dielectric mirrors were fabricated with the electron beam evaporation technique and the ITO layers were deposited by means of magnetron sputtering.

The ferroelectric in the TFI resonator was a lead lanthanum zirconate titanate (PLZT) thin film material deposited by means of the metal-organic chemical liquid deposition (MOCLD) technique. The photograph shown in Fig. 4 is a scanning electron microscopic (SEM) cross-sectional view of a TFI device fabricated with the described method. As shown in the picture, all the layers are well joined to form the optical resonator.
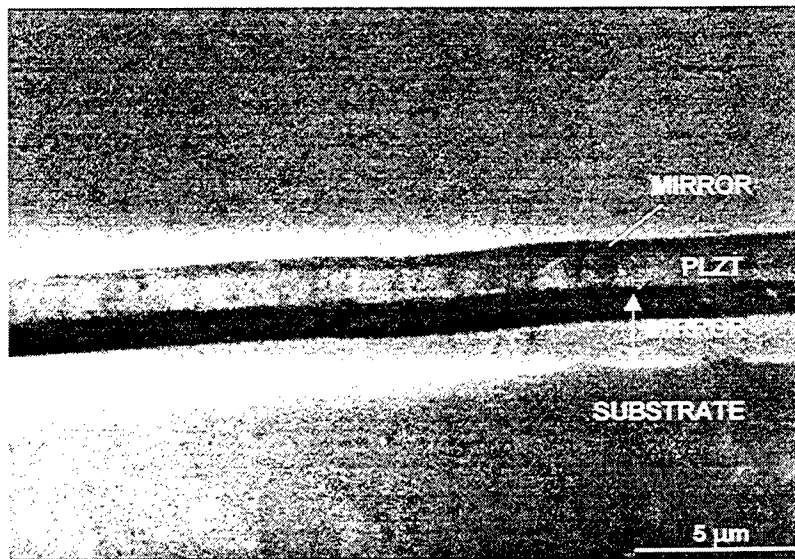

Figure 4. Scanning-electron-microscopic (SEM) photograph of the cross section of a TFI device fabricated on sapphire substrate.

Passive arrays of TFI phase modulators have been fabricated with the described technique. The sizes of the modulator pixels ranged from 10 μm × 10 μm to 200 μm × 200 μm. A 2×8 passive array on a sapphire substrate is shown in Fig. 5. The size of each pixel is 25 μm × 25 μm. The square pixels (at the center of the photograph) are connected to the fan-out metallic contacts shown in dark color. These arrays were packaged and wire bonded. Fig. 6 shows a packaged 2×8 modulator array sitting on its electronic controller box. Each individual pixel can be controlled by a modulating voltage independent of other pixels.
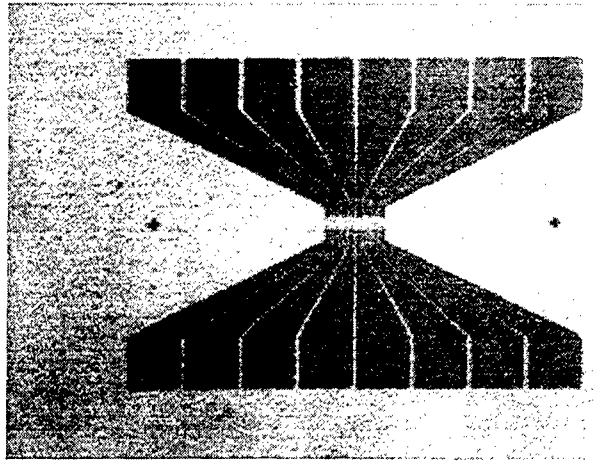
Figure 5. TFI phase modulator array fabricated on sapphire substrate. An array of 2×8 pixels is shown. The active area of each pixel is 25 μm ×25 μm. The metallic contacts are shown in dark color.
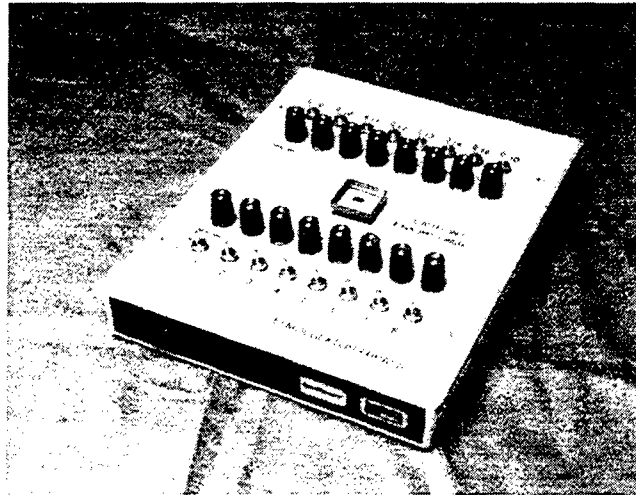

Figure 6. Packaged TFI phase modulator array with controller. Each individual pixel can be controlled by a modulating voltage independent of other pixels.

4. PERFORMANCE OF THE TFI PHASE MODULATOR

As the TFI modulators are fabricated on transparent substrates such as sapphire, some device characteristics can be measured easily from the transmitted light before packaging. As was discussed earlier, an ideal TFI phase modulator reflects all the light energy. Because of the imperfection of the bottom mirror, practical devices often pass a measurable amount of light, which can be used to characterize the device in terms of its optical quality, the finesse of the resonator and its tunability. Shown in Fig. 7 is the spectral transmission of a TFI phase modulator. For the measurement, a beam of while light was focused onto the device and the transmitted light was analyzed with a monochrometer. As shown by the data, the full width at half maximum (FWHM) of the transmitted peak is approximately 2.3 nm, which corresponds to a resonator finesse of 18. The peak transmission at the resonant wavelength is shown to be less than 5%, indicating that the reflected light may suffer approximately 5% light energy loss. The tunability of the device is clear demonstrated by the shift of the peak transmission wavelength under voltage. As shown, with 40 volts a shift of 0.7 nm was measured. A phase shift of approximately 0.5π is estimated in the reflected light under the voltage.
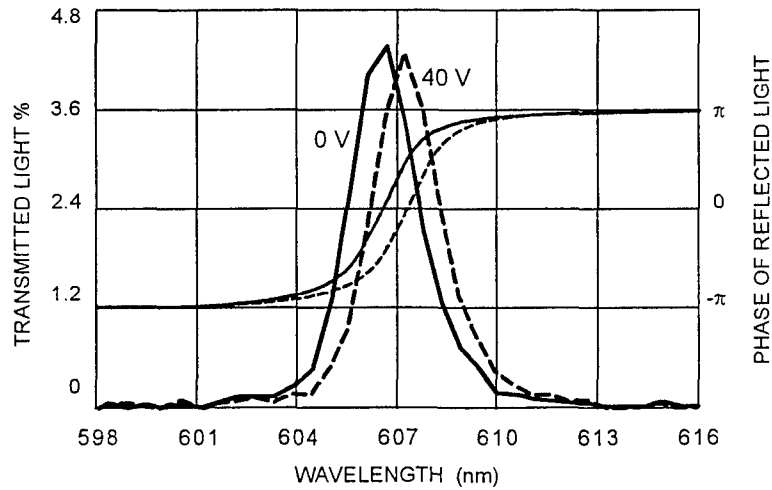
Figure 7. Characteristics of a TFI phase modulator, measured via its spectral transmission.

Direct characterization of the phase modulation from the fabricated TFI arrays was carried out with the Mach-Zehnder interferometer shown in Fig. 8. A He-Ne laser with 632.8-nm emission was used as the light source and focused onto one of the modulator pixels. The light reflected from the modulator was collimated and let interfere with the reference beam. With this arrangement the light intensity detected is proportional to $I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$, where I_1 and I_2 is the intensity of the reference beam and the modulated beam (reflected from the device), respectively; ϕ is the phase difference between the two light beams. For the convenience of measurements, the constant relative phase between the two beams was adjusted so that the modulation signal was proportional to $\sin\phi$. The system was calibrated by recording the intensity modulation corresponding to a full π phase shift introduced manually.
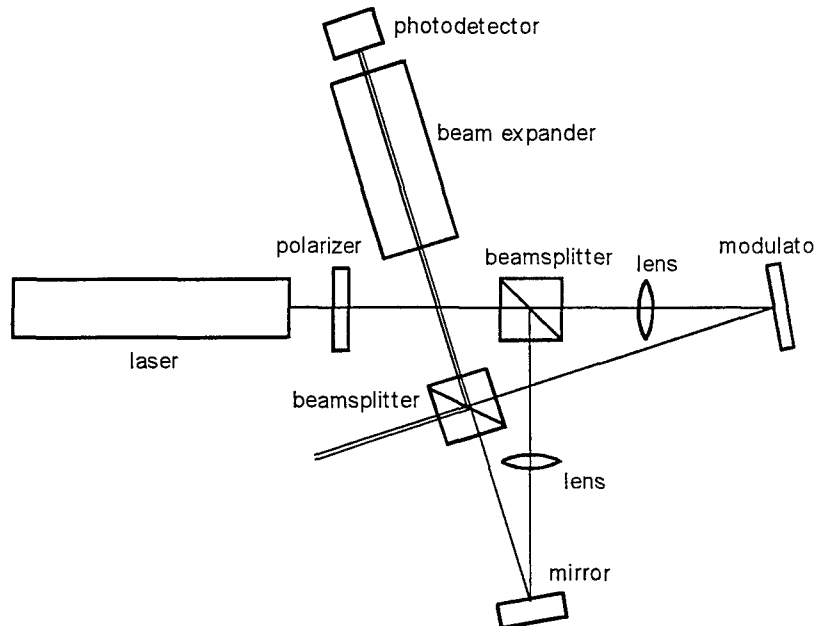

Figure 8. Experimental setup for characterizing the TFI reflective phase modulators.

The phase modulation from a TFI pixel was recorded when a sinusoidal voltage signal was applied to the modulator. Shown in Fig. 9 is the measured phase shift as a function of the applied voltage and phase modulation with time. The phase

shift as a function of the voltage, Fig. 8(a), shows an asymmetric hysteresis loop which is a manifestation of the asymmetric ferroelectric hysteresis loop, commonly observed from thin film ferroelectrics. As shown by the data, the modulator under an applied voltage of -45 volts produced a phase shift of 0.24 radians (or 13.7 degrees). This phase shift is small compared to a calculated value of 1.3π for a device with a ferroelectric layer that possesses a quadratic electrooptic coefficient of 0.5×10^{-16} $(m/V)^2$. We attribute the discrepancy to the imperfection of the fabricated Gires-Tournois resonator and the fact that the electrooptic coefficient for ferroelectric films in the cavity is often lower than that of materials grown on bare sapphire substrates.
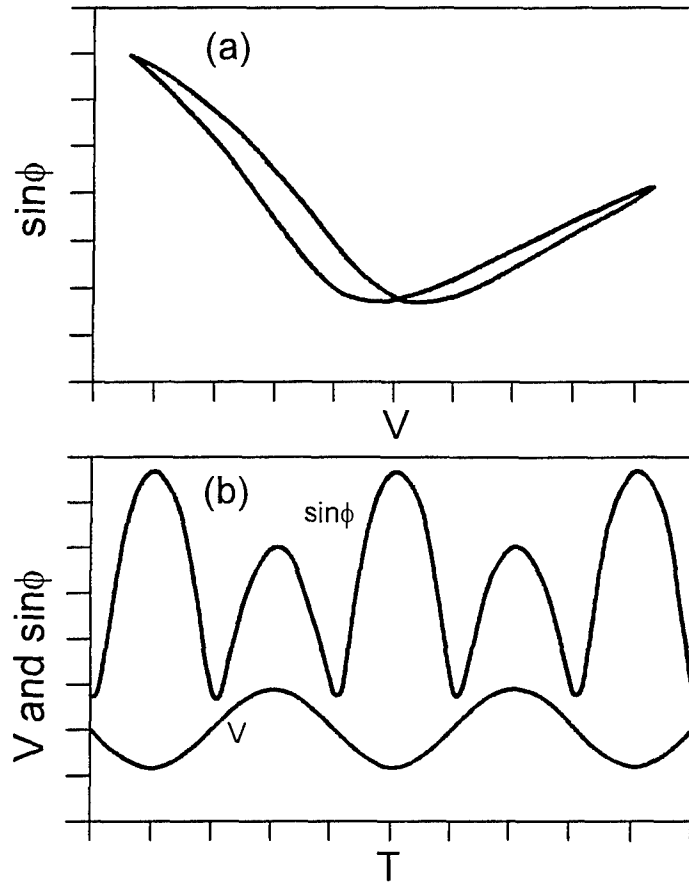

Figure 9. Phase modulation measured from a single pixel TFI phase modulator. (a): phase change as a function of the applied voltage; the x-axis is 10 volts per division and the y-axis is 0.045 per division. (b): phase modulation with time responding to the sinusoidal voltage signal; the x-axis is 250 µs per division and the y-axis is 0.045 per division for the phase shift and 50 volts per division for the voltage.

5. TFI LASER BEAM STEERING DEVICE

An application of the TFI optical phase modulator is laser beam steering. Two types of laser beam steering devices can be fabricated. The first type is based on modulator arrays similar to what is shown in Fig. 5. For laser beam steering modulator elements in the shape of long and narrow strips should be densely arranged. Since each individual element can provide a phase shift in the range of $-\pi$ and π, one can program the voltages applied to each individual element so that a quasi-linear phase variation is obtained across the diameter of a laser beam, thus the reflected beam is steered. As the TFI phase modulators are comprised of thin film structure, pitch length as small as 2 µm between pixels is possible. With small pitch length the device creates few diffraction side lobes.

Another type of laser beam steering device with TFI uses a single deflection element. The structure of the device is shown in Fig. 10. In the device, a sheet resistor is used in place of the top conductive layer for devices described in the preceding sections. This sheet resistor serves to create an electric field gradient inside the ferroelectric thin film material. The field

gradient in turn causes a variation of the phase deviation $\Delta\phi$ across the diameter of the laser beam. According to Eq. (1), a small spatial distribution of $\Delta\phi$ creates a optical phase distribution approximated by:

$$\Phi = -2\frac{1+\sqrt{R}}{1-\sqrt{R}}\Delta\phi .$$

(2)

If the sheet resistor generates a linear spatial distribution of $\Delta\phi$, the reflected laser beam will also possess a linear phase distribution governed by the above equation, the reflected beam is then deflected. Because the continuous phase variation in the device is limited to the range of $-\pi$ and π, substantial beam deflection angle can only be achieved for focused laser beam with the single element device, while the arrayed deflector is capable of steering unfocused laser beams with larger beam sizes.
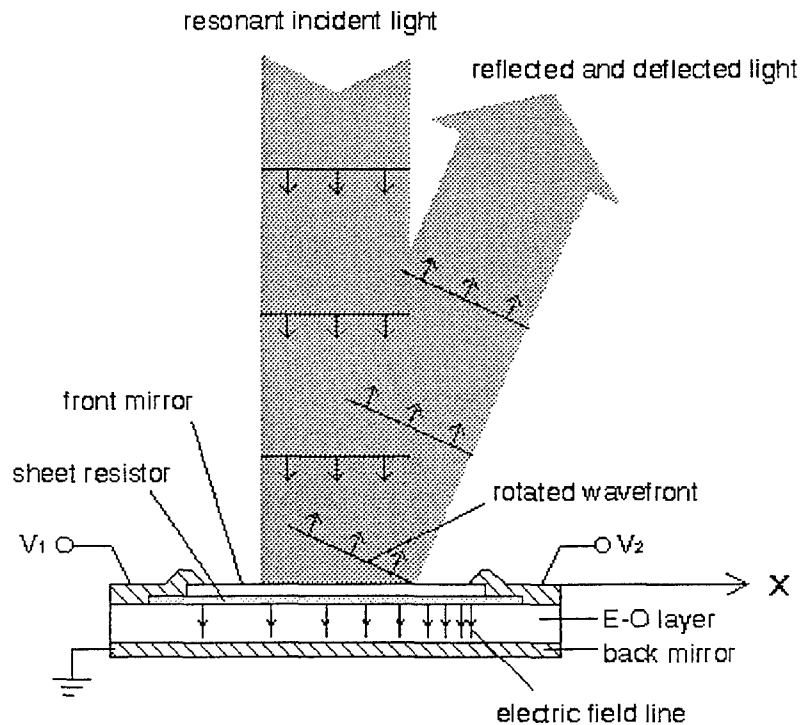

Figure 10. Structure of single-element TFI laser beam deflecting device. A sheet resistor is used in place of the conducting layer in the phase modulator. As differential voltages are applied to the two terminals of the sheet resister an electric field gradient is created inside the ferroelectric thin film material so that a wavefront rotation is achieved.

The single-element TFI beam steering devices have been fabricated using the techniques similar to what were used for the phase modulator arrays described previously. The sheet resistor was formed using a modified ITO thin film material with resistance of approximately 100 kΩ/$\square$. Shown in Fig. 11 is a microscopic photograph of a single-element TFI beam steering device on a sapphire substrate. The device has an active area of 50 μm × 50 μm. The triangle-shaped electrodes connect the sheet resistor to the two metallic contacts (one contact area is shown). The thickness of the PLZT thin film is approximately 1.2 μm, designed for deflecting He-Ne laser beam of 632.8-nm wavelength at an incident angle of 10 degrees.

In order to record the beam deflection, a charge-couple device (CCD) camera was set to intercept the laser beam reflected from the device. As a differential voltage was applied to the sheet resistor the position where the light impinged on the CCD camera was recorded. As shown in the lower portion of Fig. 11, the laser beam profile shifted for 4 mm as a differential voltage of 30 volts was applied to the device. The distance between the beam steering device and the CCD camera was 180 mm. The measured spatial shift corresponds to a deflection angle of 1.3 degrees.
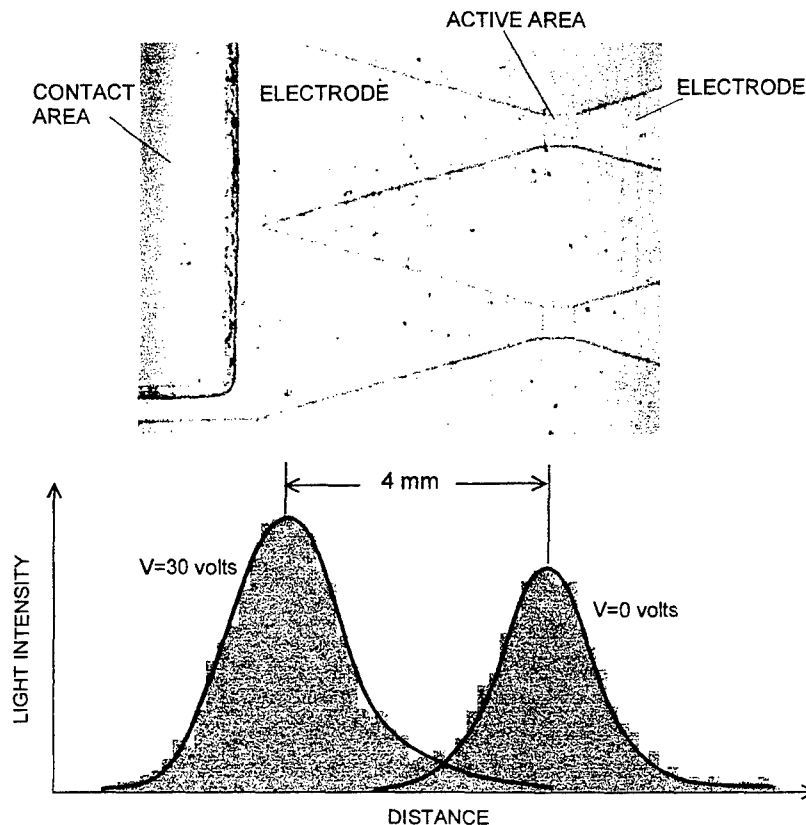
Figure 11. Single-element TFI laser beam steering device. The upper portion is a microscopic photograph of a device with 50 μm × 50 μm active area. The lower portion shows the deflection of the reflected light beam, recorded with a CCD camera intercepting the beam path.

6. CONCLUSION

The preliminary device types described in this paper show that the TFI devices represent a viable technology for laser light modulation and laser beam steering. The complex-oxide ferroelectric thin film materials, such as the PLZT materials, in the TFI resonator can produce large voltage-controlled refractive index change, second only to liquid crystal materials. The response speed of the complex-oxide ferroelectric materials is much faster than that of liquid crystals. The second attractive aspect of the TFI devices is that they can be integrated with silicon-based or wide band gap GaN-based microelectronic devices monolithically. It is therefore possible to fabricate high-density, high-speed, active-matrix-controlled SLMs on semiconductor substrates for various applications.

In this paper we demonstrated two applications of the TFI devices, i.e. the phase modulator and the single-element laser beam steering device, both fabricated on sapphire substrates with the thin film processing techniques. Both devices were based on the concept of tunable Gires-Tournois etalon, in which a thin film PLZT material was used as the tunable medium. Passive arrays of TFI phase modulators were fabricated and packaged. The phase modulators were characterized by means of their spectral transmission, and by the use of a Mach-Zehnder interferometer. Deflection of a He-Ne laser beam was demonstrated with the single-element TFI beam steering device. Substantial improvements in these devices are expected as the material and device processing techniques become more mature.

REFERENCES

1. K. M. Johnson, D. J. McKnight, and I. Underwood, "Smart spatial light modulators using liquid crystal on silicon," *IEEE J. Quantum Electron.* **29**, pp. 699-714, 1993.
2. D. J. McKnight, K. M. Johnson, and R. A. Serati, "256×256 liquid-crystal-on-silicon spatial light modulator," *Appl. Opt.* **33**, pp. 2775-2784, 1994.

3. P. Tayebati, C. Hantzis. and E. Canoglu, "An optically addressed modulator based on low-temperature-grown multiple quantum well GaAlAs," *Appl. Phys. Lett.* **71**, pp. 446-448, 1997.

4. T. H. Lin, A. Ersen, J. H. Wang, S. Dasgupta, S. Esener, and S. H. Lee, "Two-dimensional spatial light modulators fabricated in Si/PLZT," *Appl. Opt.* **29**, pp. 1595-1603, 1990.

5. M. S. Jin, J. H. Wang, V. Ozguz, and S. H. Lee, "Monolithic integration of a silicon driver circuit onto a lead lanthanum zirconate titanate substrate for smart spatial light modulator fabrication," *Appl. Opt.* **33**, pp. 2842-2848, 1994.

6. F. Wang and G. H. Haertling, "Large electrooptic modulation using ferroelectric thin films in a Fabry-Perot cavity," in *Proceedings of the Ninth IEEE International Symposium on Applications of Ferroelectrics,* pp. 683-686, 1994.

7. F. Wang and G. H. Haertling, "Integrated reflection light modulator using a ferroelectric thin film material on silicon," in *Conference on Lasers and Electro-Optics,* Vol. 15 of 1995 OSA Technical Digest Series (Optical Society of America, Washington, D. C., 1995), paper CThI22.

8. F. Wang, D. Tsang, H. Jiang, K. K. Li, and V. Fuflyigin, "Ferroelectric-on-silicon modulators for high density optical interconnects," in *Conference on Lasers and Electro-Op*tics, Vol. 6 of OSA Technical Digest (OSA, Washington, D.C. 1998), p. 141.

9. F. Wang, K. K. Li, V. Fuflyigin, H. Jiang, J. Zhao, P. Norris, and D. Goldstein, "Thin ferroelectric interferometer for spatial light modulation," *Appl. Optics* **37**, pp. 7490-7495, 1998.

10. P. L. Pondillo, K. K. Li, F. Wang, and M. Cronin-Golomb, "Spatial light modulation using a thin ferroelectric interferometer," *OSA Technical Digest on Spatial Light Modulators and Integrated Optoelectronic Arrays,* April 12-14, 1999, Aspen, Colorado, p. 103.

11. The fundamentals of Gires-Tournois etalon can be found in monographs such as A. Yariv and P. Yeh, *Optical Waves in Crystals* (Wiley, New York, 1984), pp. 290-293.

12. K. K. Li, G. H. Haertling, and W.-Y. Howng, "An automatic dip coating process for dielectric thin and thick films," *Integrated Ferroelectrics* **3**, pp. 81-91, 1993.

13. V. Fuflyigin, K. K. Li, F. Wang, H. Jiang, S. Liu, J. Zhao, P. Norris, and P. Yip, "Preparation of ferroelectric oxide films by sol-gel method," *High-Temperature Superconductors and Novel Inorganic Materials,* G. Van Tendeloo *et al.* Eds, (Kluwer Academic Publishers, Netherlands).

14. Y. Lu, G. H. Jin, M. Cronin-Golomb, S. W. Liu, H. Jiang, F. Wang, J. Zhao, S. Q. Wang, and A. J. Drehman, "Fabrication and Optical Characterization of $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ Planar Thin Film Optical Waveguides," *Appl. Phys. Lett.* **72**, 2927-2929, 1998.

15. F. Wang, "Calculation of the Electro-Optical and Nonlinear Optical Coefficients of Ferroelectric Materials from Their Linear Properties," *Phys. Rev. B.* **59**, pp. 9733-9736, 1999.

16. G. H. Haertling, "PLZT electrooptic materials and applications — a review," *Ferroelectrics* **75**, pp. 25-55, 1987.